

Advancements for Active Remote Sensing of Carbon Dioxide from Space

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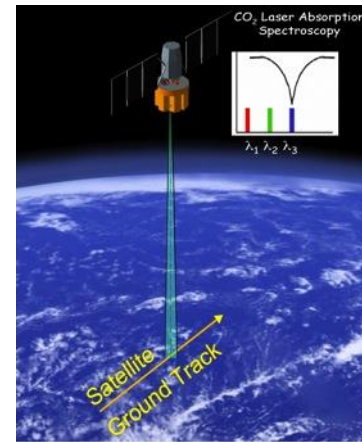
³Science Systems and Applications, Inc. (SSAI)

⁴Exelis Inc.

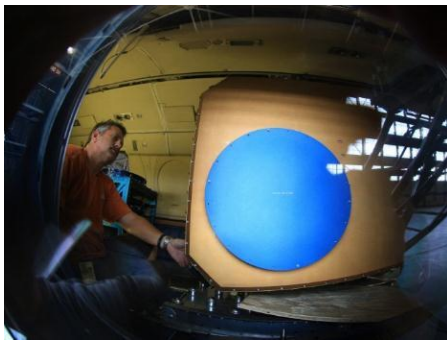
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**4th International
Symposium on Atmospheric
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Remote Sensing
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NASA Langley Lidar Sensors

Ground
Based
Lidar

Electra

LASE

LITE

CALIPSO

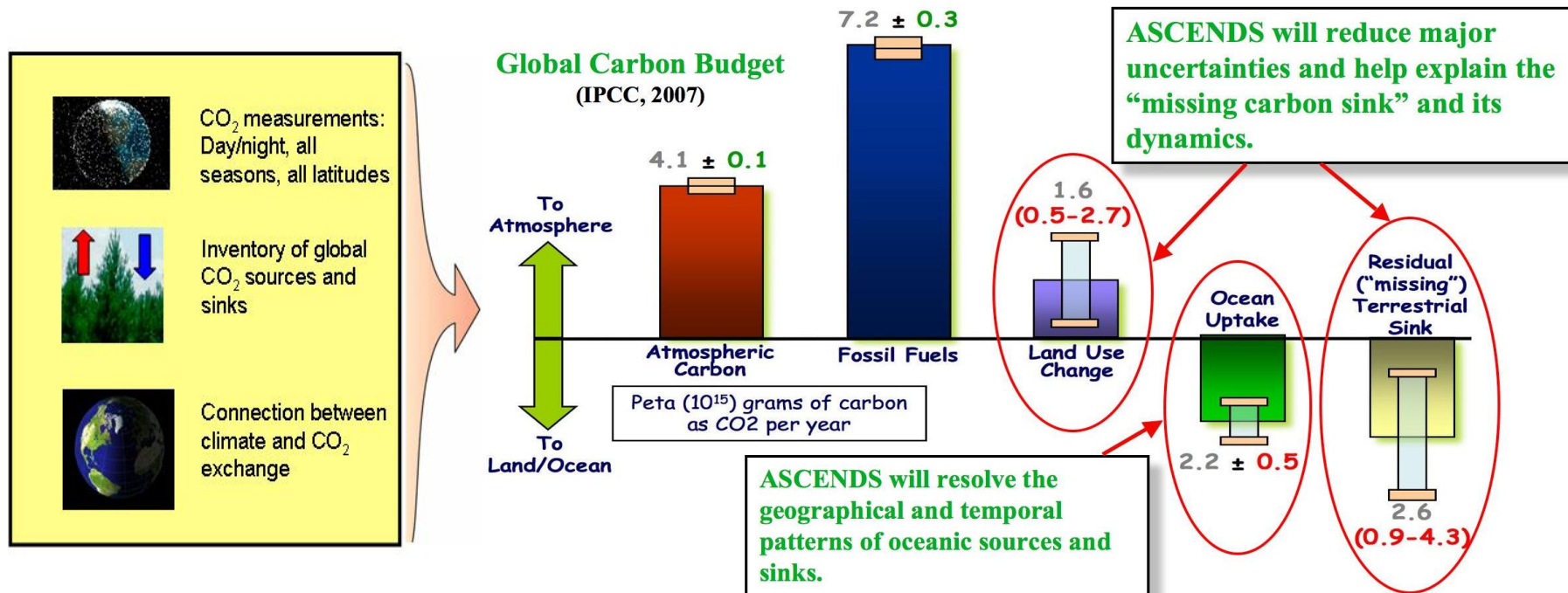
CO₂ DIAL
(ASCENDS)

Program, carrier	Circa	Channels	Laser(s) (*tunable)	Measurement or Species
Gnd. Based 48 inch	1970	2	ruby @347 & 694 nm	Aerosols/ N ₂
Aircraft, Electra 990	1978	3	Ruby, YAG, YAG/ Dye @ 1064, 720*, 694, 600*, 532 347, 300* nm	Aerosols H ₂ O/O ₃
LASE, ER-2	1994	3	Ti:Al ₂ O ₃ @815 nm	H ₂ O/Aerosols
LITE, Shuttle	1994	3	YAG @ 1064, 532, 355 nm	Aerosols/ Density
CALIPSO	2006	2	Nd:YAG	Aerosols/ Clouds
ASCENDS	2022	3	1.57 μ m Fiber Laser	CO ₂



Active Sensing of CO₂ Emissions over Nights, Days, and Seasons (ASCENDS)

2007 NRC Decadal Survey:
Earth Science & Applications from Space; Tier II Mission



- ASCENDS provides a accurate global dataset of atmospheric CO₂ column measurements without seasonal, latitudinal, or diurnal bias.

- These measurements will be used in retrieval of CO₂ fluxes to estimate *regional* carbon sources/sinks and thereby improve understanding of underlying mechanisms to improve climate predictions.



Instrument Development: Langley and Exelis, Inc.

14 MFLL + 1 ACES flight campaigns

Multifunctional Fiber Laser Lidar (MFLL)

- Developed by ITT/Exelis in 2004, and advanced by Exelis and Langley since 2005
- 14 proof-of-concept field campaigns



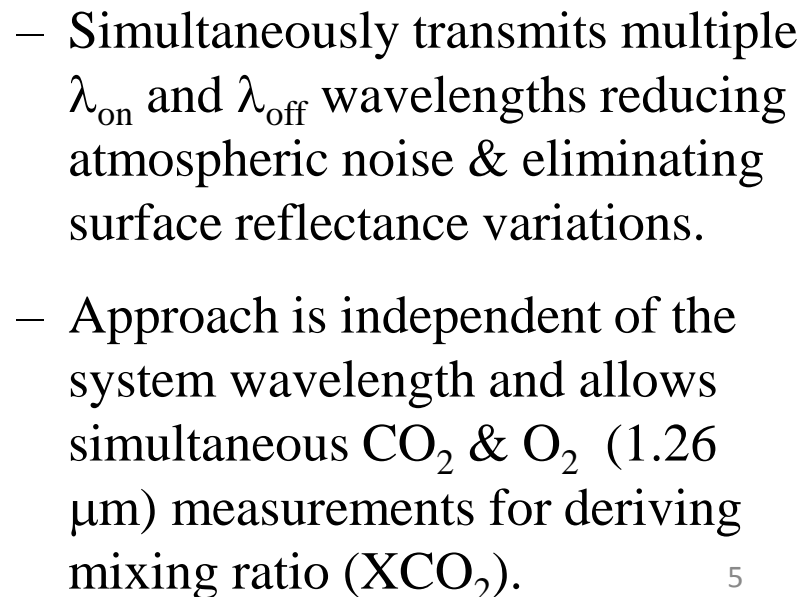
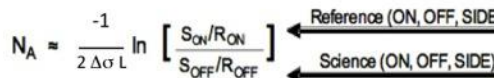
MFLL integrated on DC-8

ASCENDS CarbonHawk Experiment Simulator (ACES)

- Developed at Langley with technical support from Exelis
- Advancing key technologies for spaceborne measurements of average CO₂ column mixing ratio



ACES integrated on HU-25

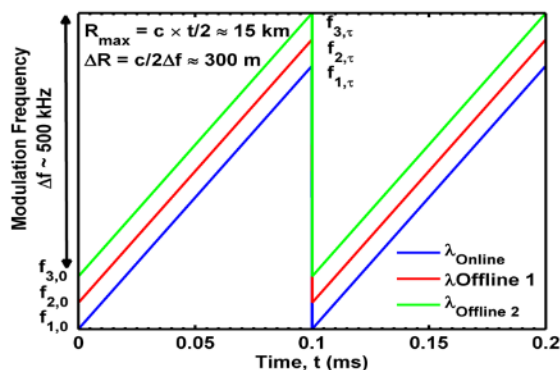
Dobler, et al., *Applied Optics*, 2013



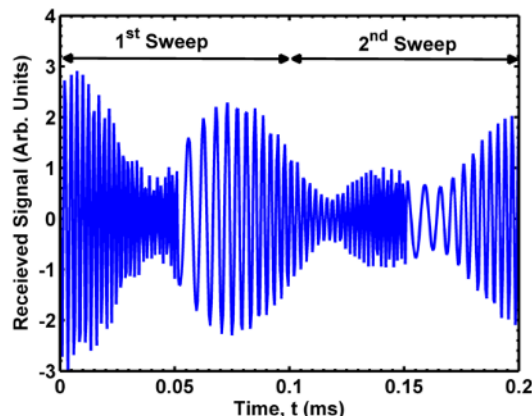
Intensity-Modulated Continuous-Wave (IM-CW) Measurement Technique

Progression of Transmitted and Received Intensity-Modulated Waveforms

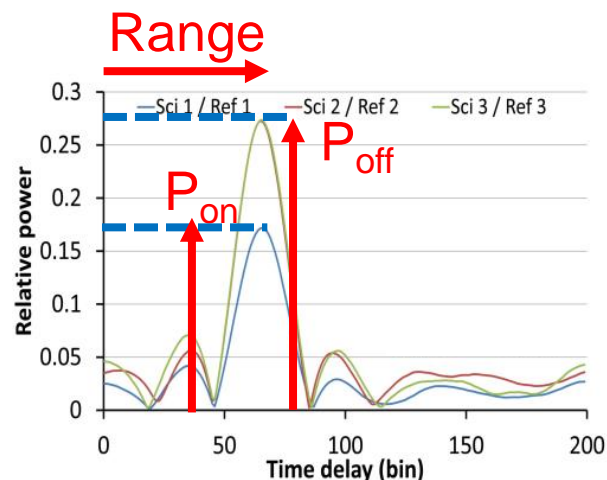
Simultaneously-transmitted intensity modulated range encoded waveforms



Simultaneously-received Online and Offline IPDA returns



Measurement: Output of correlation between transmitted and received waveforms



Range-encoded approach for detection and ranging is analogous to mature Frequency-Modulated Continuous Wave (FM-CW) Radar and GPS measurement techniques

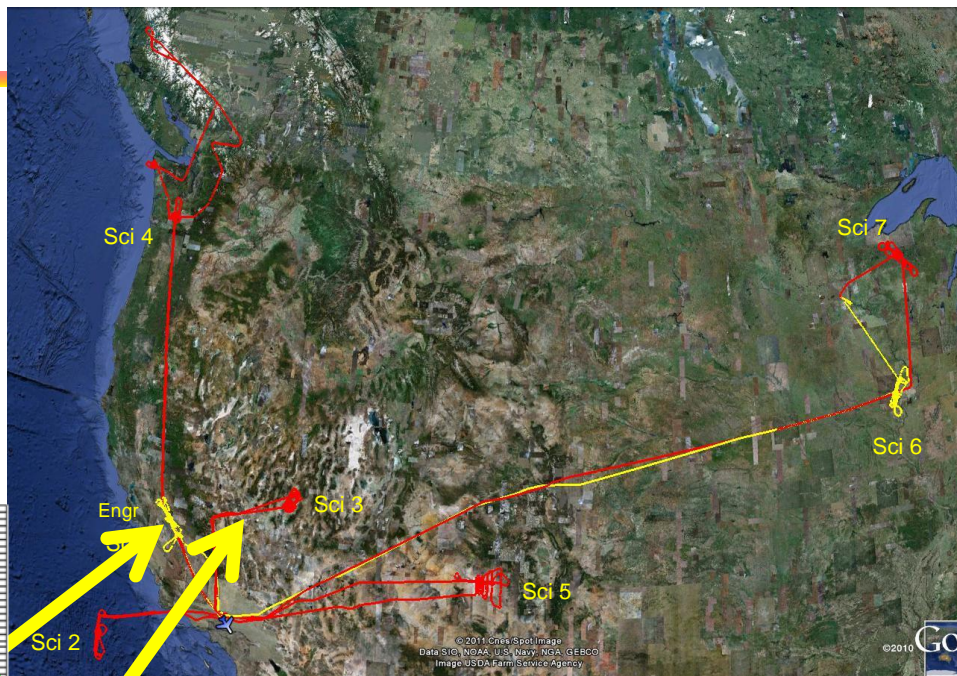
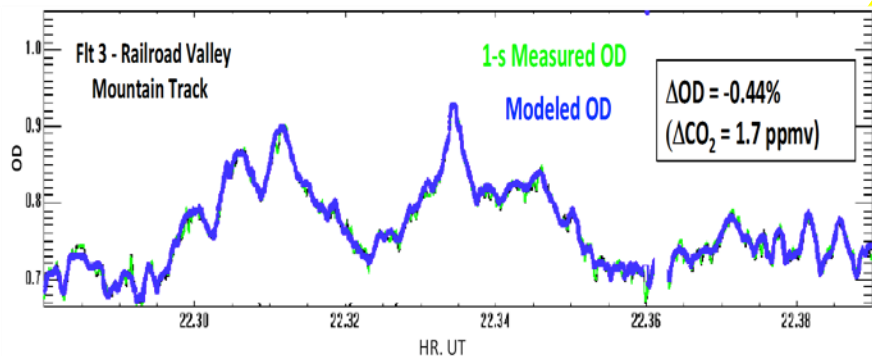
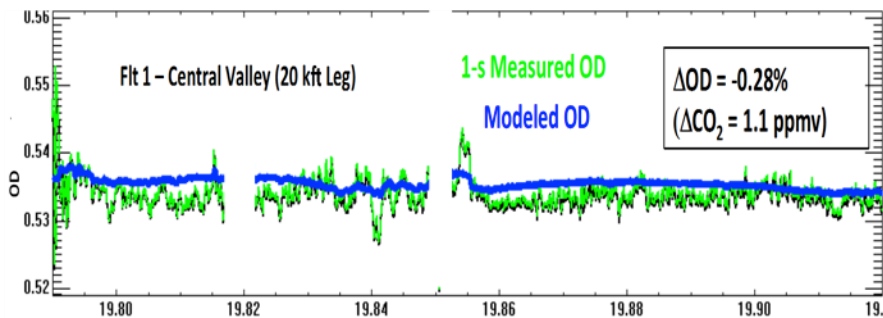
$$DAOD = \frac{1}{2} \ln \left(\frac{P_{\text{off}} * E_{\text{on}}}{P_{\text{on}} * E_{\text{off}}} \right)$$



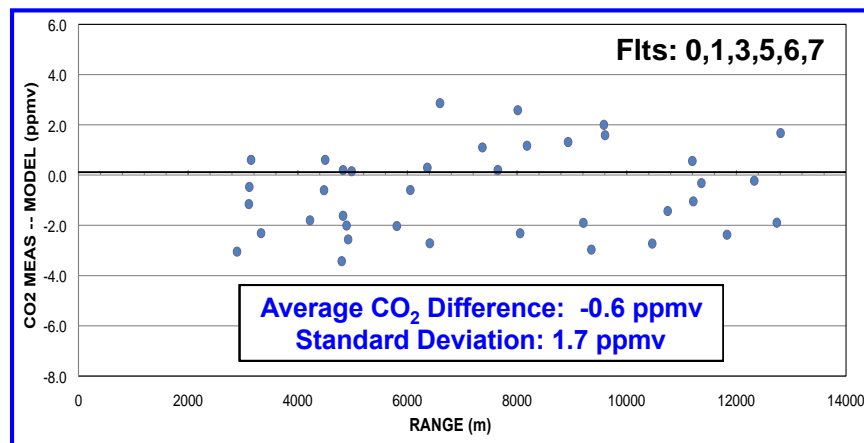
MFL Optical Depth Comparisons: ASCENDS DC-8 Campaign 28 July – 11 August, 2011



Optical Depth (OD) Comparisons



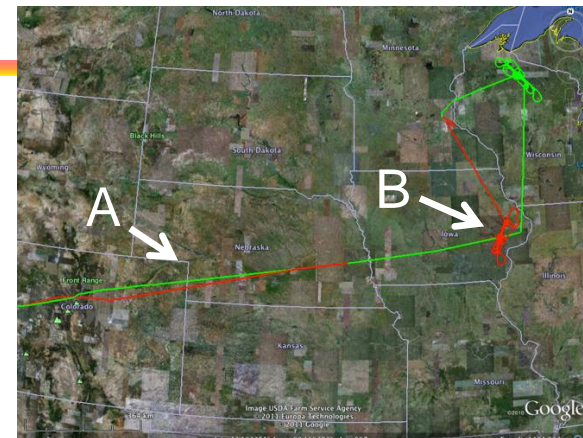
All OD Comparison Differences (Measured – Modeled)



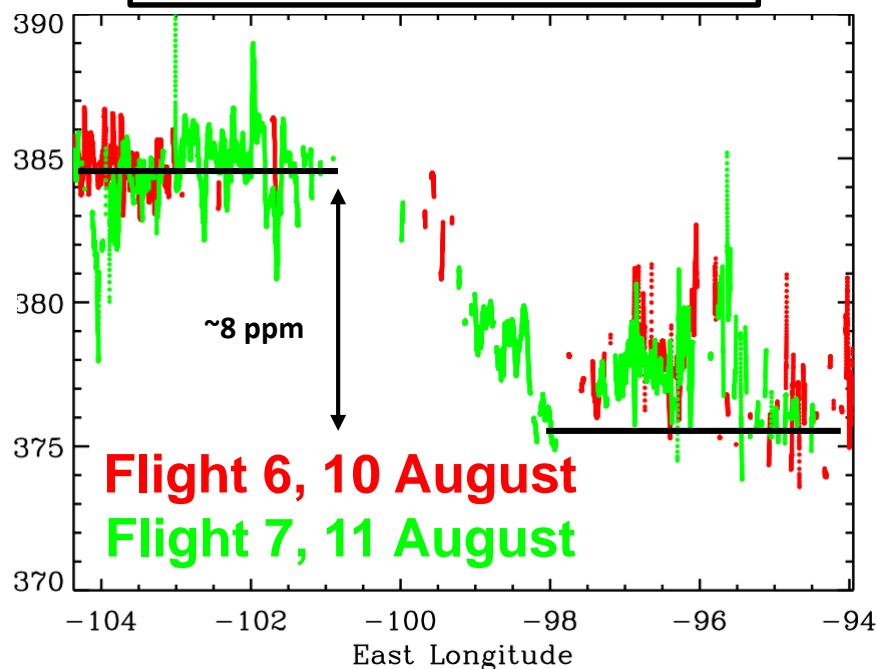


MFL 2011 and 2014 measurements: Agricultural Respiration

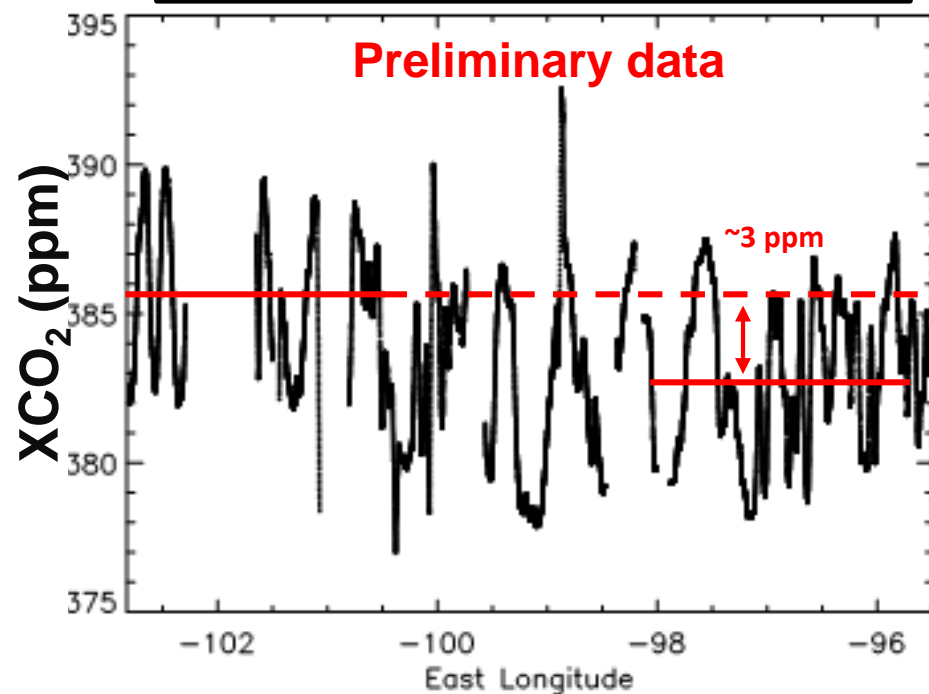
- Column CO_2 measurements over Midwestern US farm fields showed much larger drawdown signal in 2011 campaign (~ 8 ppm) compared with measurements in 2014 (~ 3 ppm)
 - Resulting from different corn growth periods and meteorological states



2011 Midwest Flights



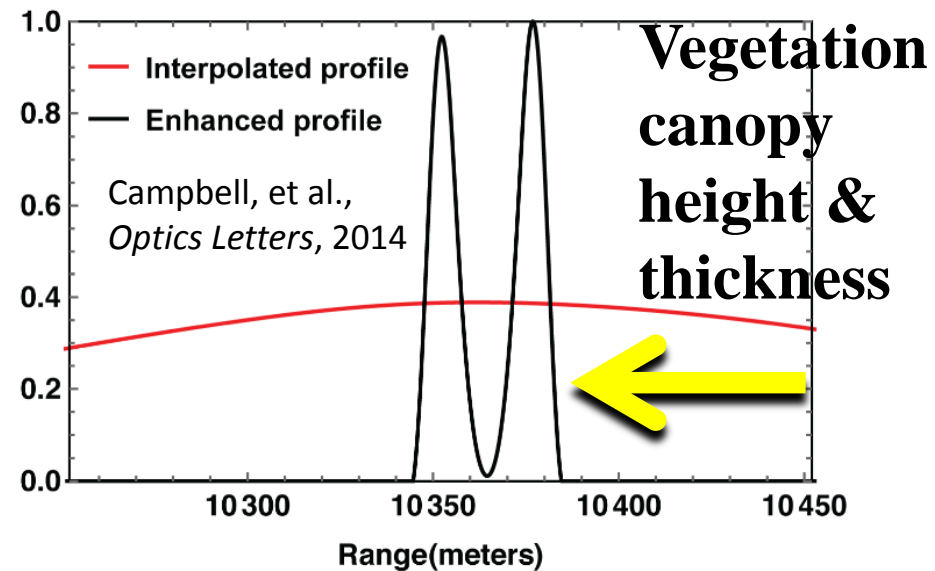
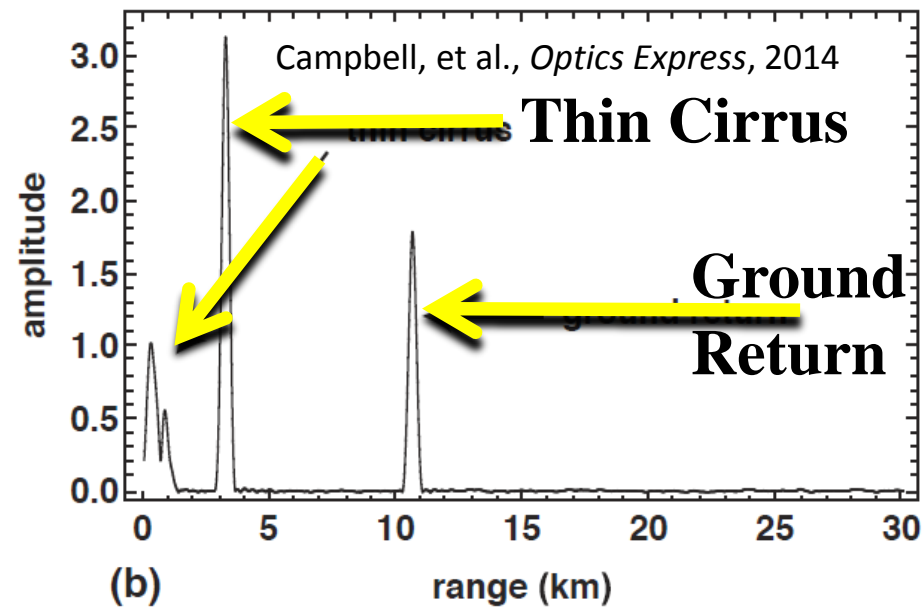
25 August 2014 Midwest Flight



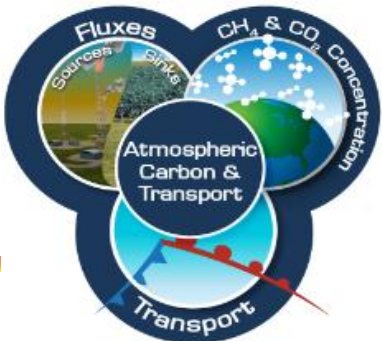


ACES 2014 Test Flights: Preliminary Ranging Results

IM-CW technique accurately retrieves range over a variety of surfaces and in the presence of optically thin clouds allowing for retrievals of column CO_2 mixing ratios to surface and cloud tops.



- Advanced deconvolution techniques resolve cloud and forest features

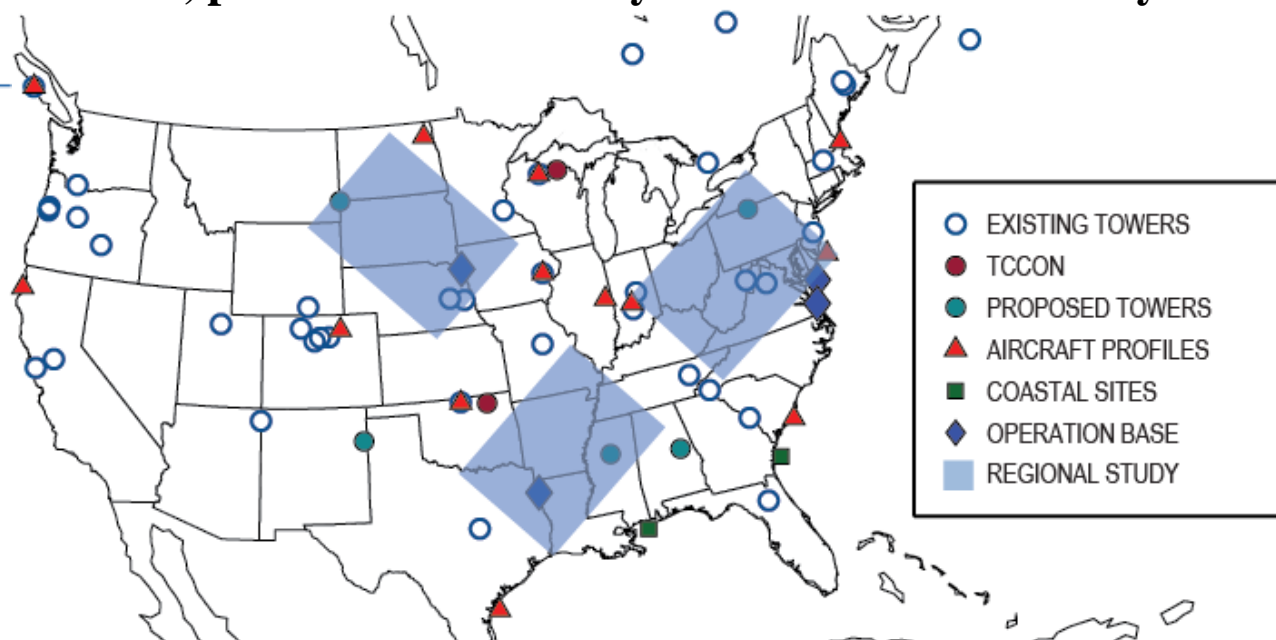


Atmospheric Carbon and Transport - America (ACT-America)

PI: Ken Davis, Pennsylvania State University

Our goals address the three primary sources of uncertainty in atmospheric inversions – transport error, prior flux uncertainty and limited data density

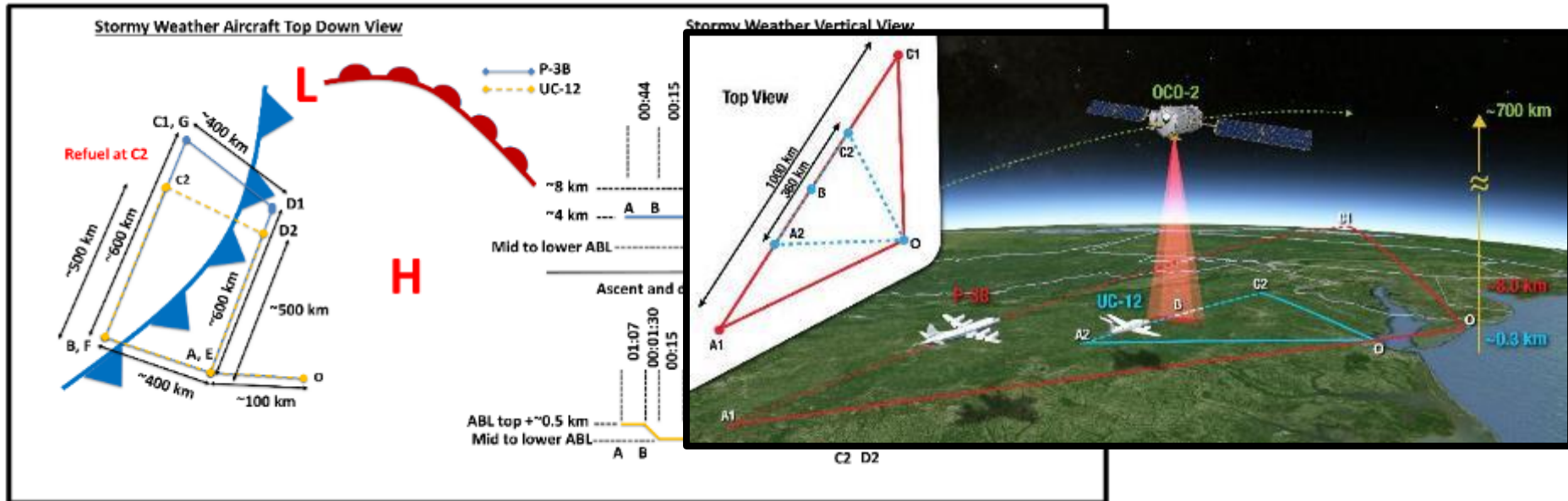
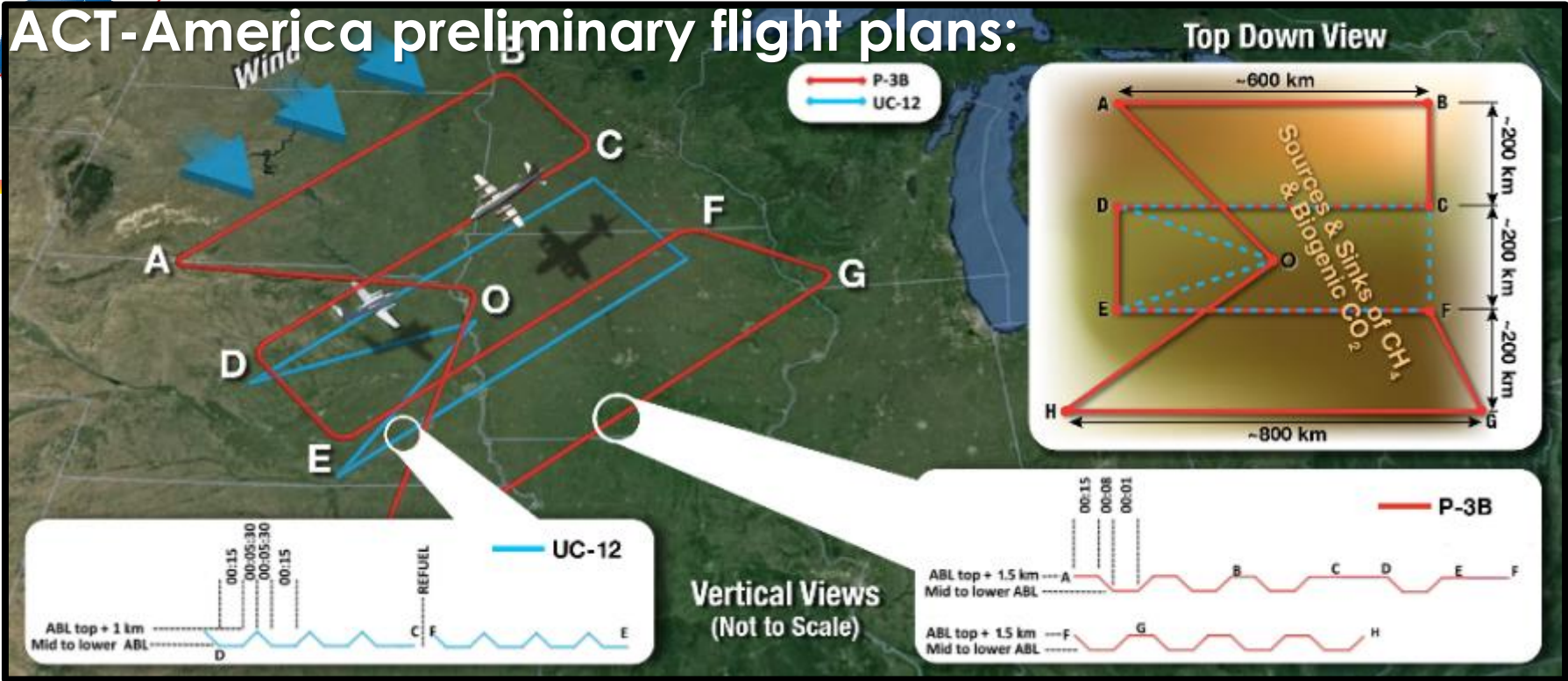
PENNSTATE



- Five, six-week campaigns over 3 years, covering each season and summer twice
- 2 aircraft: C-130 (MFL, Cloud Physics Lidar, in situ instruments) & UC-12 (in situ instr.)
- 2 weeks in each region (Wallops/Langley, Sioux City, and Shreveport)

Fall 2015	Win 2016	Spr 2016	Sum 2016	Fall 2016	Win 2017	Spr 2017	Sum 2017	Fall 2017	Win 2018	Spr 2018	Sum 2018	Fall 2018
	X		X			X		X			X	

ACT-America preliminary flight plans:





Summary

- NASA Langley Research Center has a long history of successfully designing and implementing airborne and spaceborne lidar systems.
- The Exelis MFL instrument has collected airborne CO₂ column measurements in 14 campaigns since 2005 and is now preparing for the ACT-America Earth Venture Suborbital campaign.
- The ACES instrument successfully completed its first test flights in 2014, and will continue technology advancement efforts during test flights in August 2015 and January 2016.
 - HgCdTe detector/TIA bandwidth increased to ~4.9 MHz for advanced modulation waveforms
 - Increased transmitter power and receiver aperture yielding high precision measurements over varying surfaces
- Our team is continuing to advance technologies and measurement techniques critical for column CO₂ measurements from space.



Future Directions

- The ACT-America mission has begun, with five airborne campaigns planned for 2016-2018.
- Continue data analysis to fully quantify MFL and ACES instrument performances
- Continue flight testing of new modulation algorithms and hardware improvements
 - Deconvolution techniques for clouds and forest canopies
 - Operational tests of retrievals with sideline wavelengths
 - Instrument automation for UAV operations
- Continue Technology Readiness Level (TRL) advancement and space qualification of ASCENDS technologies



Acknowledgements



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Backup Slides



ACT-America data are collected by remote and in situ sensors on two aircraft:

Remote Sensors (C-130): In-Situ Sensors (C-130 and UC-12):

MFL (Exelis, Inc.):

- Column CO_2 number density
- Range to ground

Cloud Physics Lidar (NASA Goddard):

- Atmospheric boundary Layer height
- Aerosol/Cloud optical depth

In-Situ Sensors (Ground Towers):

Picarro (Pennsylvania State University):

- In situ measurements of CO_2 and CH_4

Picarro and Ozone (NASA Langley):

- In situ measurements of CO_2 , CH_4 , CO , H_2O , and O_3 number density

Flasks (NOAA):

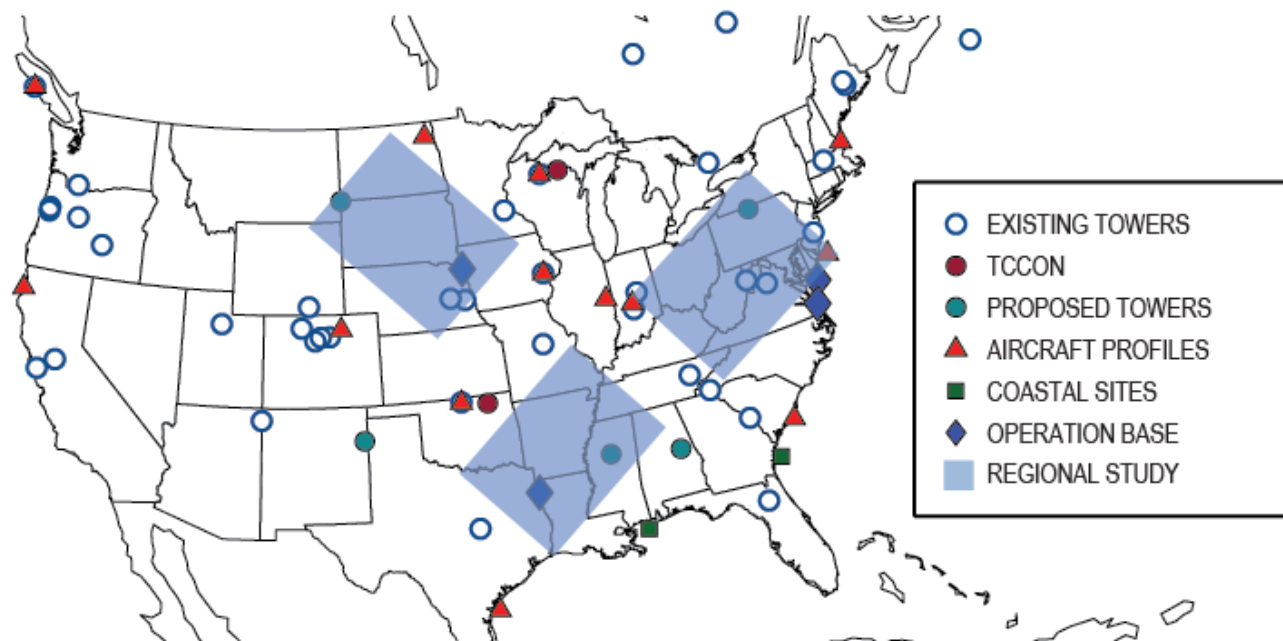
- In situ samples of CO_2 , CH_4 , CO , $^{14}\text{CO}_2$, COS





ACT-America data are collected in three regions across the eastern United States:

- Five, six-week campaigns over 3 years, covering each season and summer twice
- 2 aircraft:
 - C-130 (Wallops)
 - UC-12 (Langley)
- 2 weeks in each region (Wallops/Langley, Sioux City, and Shreveport)

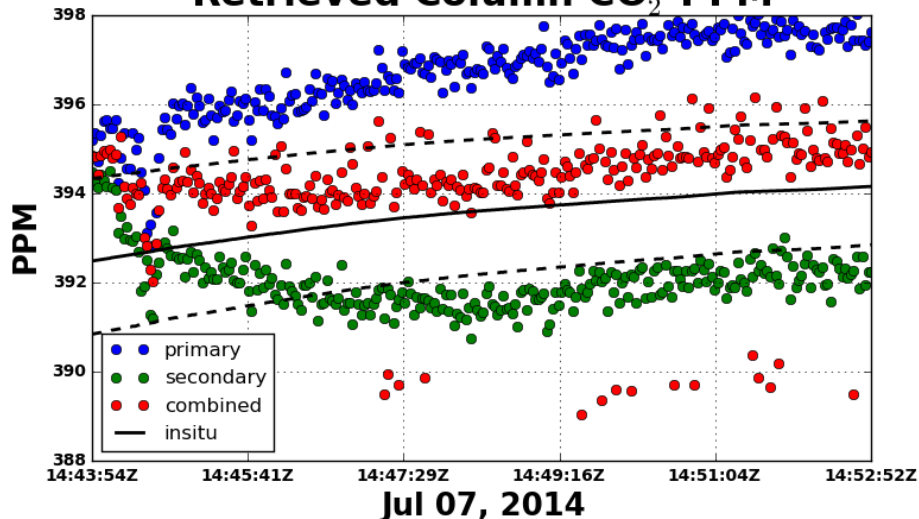


Fall 2015	Win 2016	Spr 2016	Sum 2016	Fall 2016	Win 2017	Spr 2017	Sum 2017	Fall 2017	Win 2018	Spr 2018	Sum 2018	Fall 2018
	X		X			X		X			X	

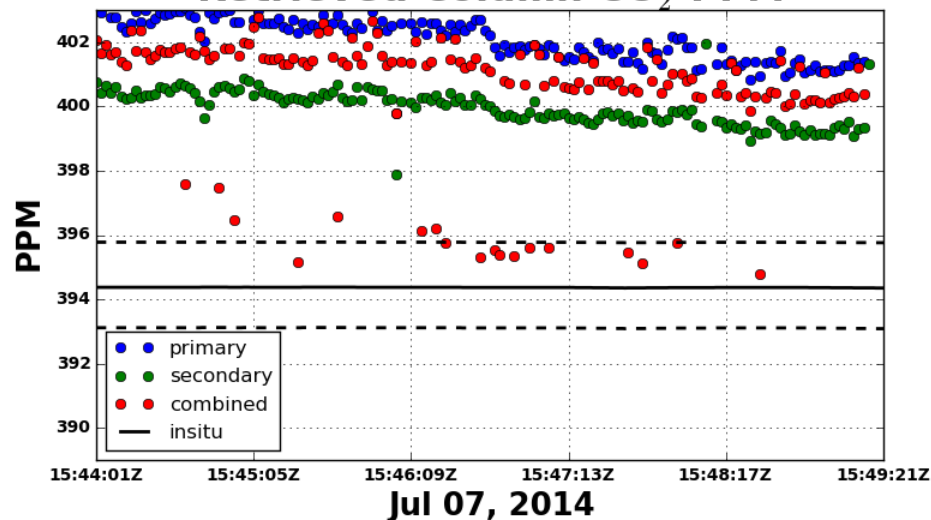


ACES 2014 Test Flights: Preliminary CO₂ Retrievals over Ocean and Land:

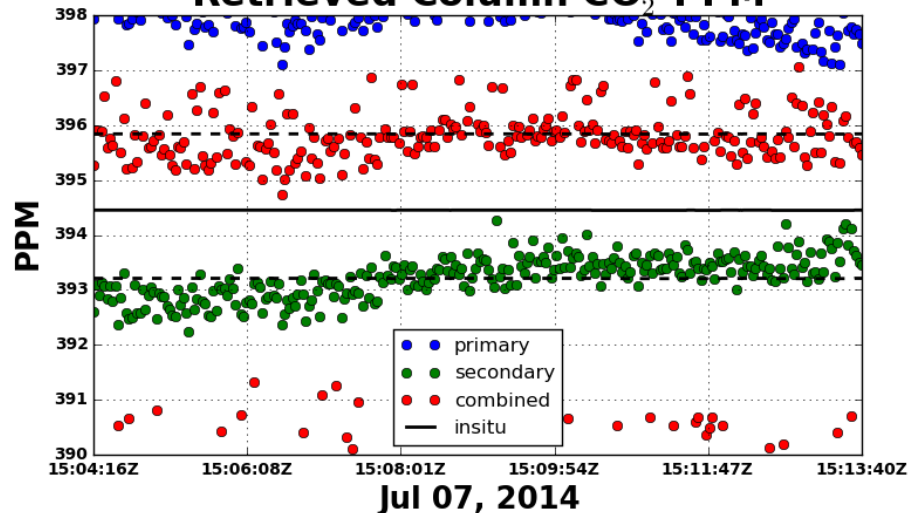
Retrieved Column CO₂ PPM



Retrieved Column CO₂ PPM

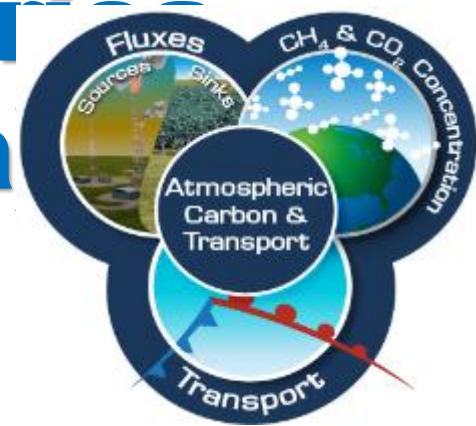


Retrieved Column CO₂ PPM



- CO₂ retrieval values (2-s average) are calibrated using primary and secondary offline wavelengths
- Average of in situ data across entire flight (binned by altitude) used for comparisons
- Actual CO₂ number densities likely different far away from spiral point and airport
- Further work is needed to compare directly with data from in situ spirals

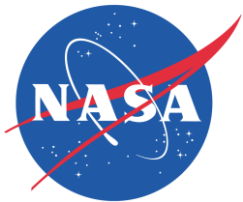
Atmospheric Carbon and Transport - America (ACT-America)



PENNSTATE



Colorado
State
University



April 2015 SD All-Hands Meeting

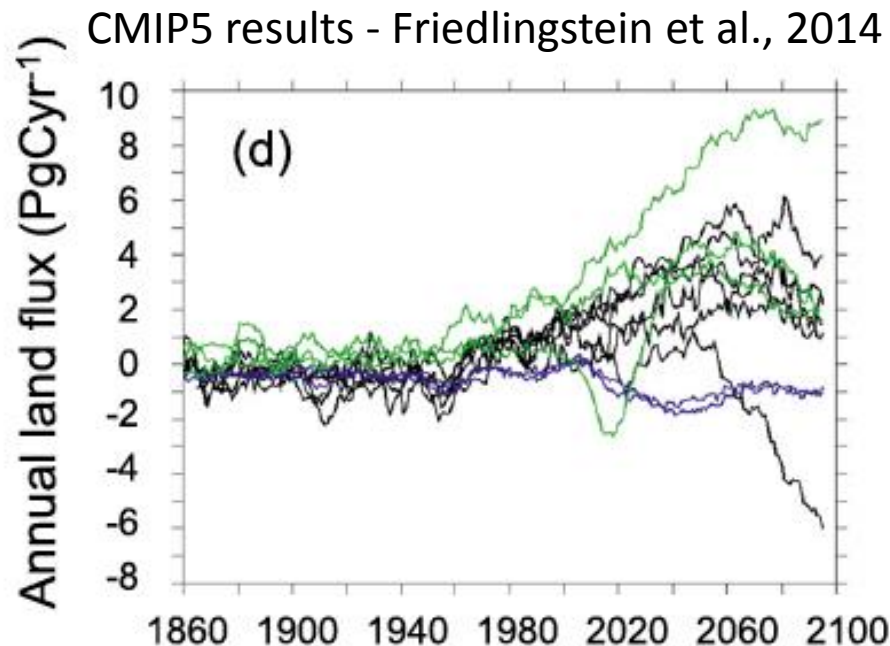
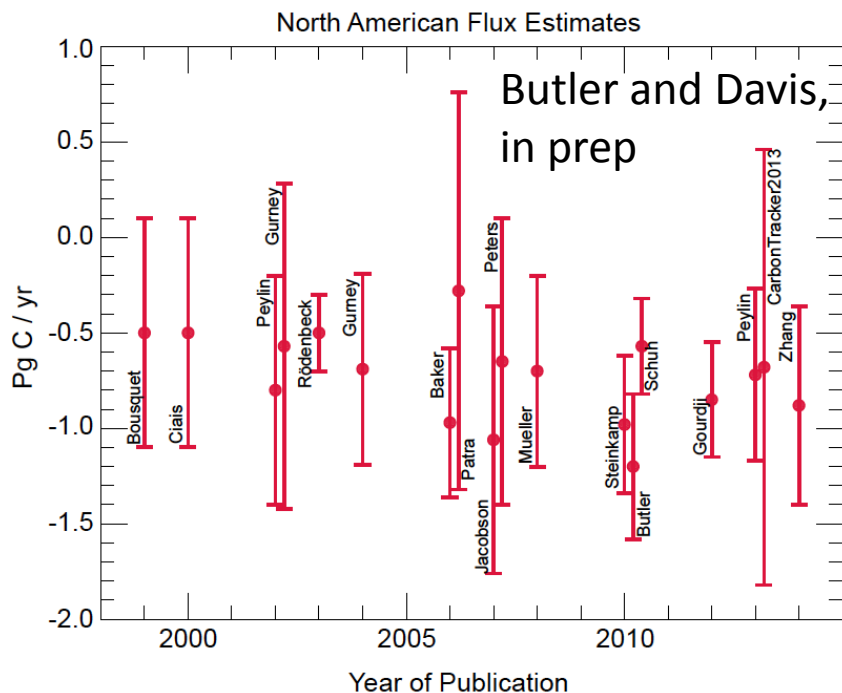
Ken Davis, Principal Investigator
Thomas Lauvaux, Deputy PI
Chris O'Dell, Deputy PI

Bing Lin, Project Scientist
Mike Obland, Project Manager
Byron Meadows, Aircraft Integration/Logistics Manager
Gao Chen, Data Manager
Amin Nehrir, Instrument Scientist
...and many others



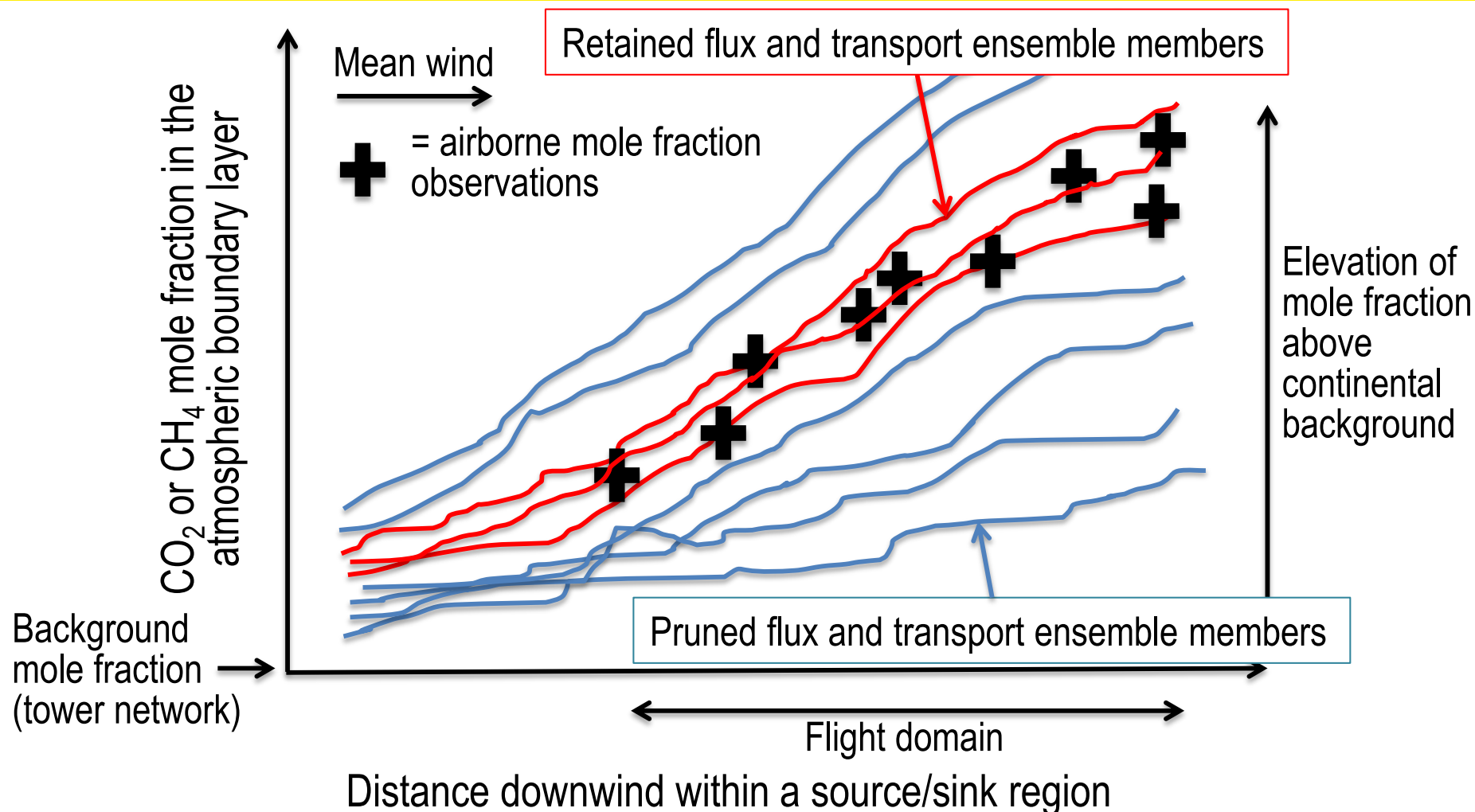
The challenge we are addressing:

- Assertion: Our inability to quantify carbon fluxes with “good” accuracy and precision across regional (larger than a flux tower footprint and smaller than the globe) domains is a *primary* methodological challenge in carbon cycle science today. It hamstrings our ability to address *all other* terrestrial carbon cycle science questions.





Simplified vision of model (flux and transport) ensemble pruning using airborne observations:



Pruned ensembles lead to more accurate and precise flux inversions using long-term GHG data (towers, flasks, satellite, NOAA airborne profiling).



ACES Scientific Motivation

The **ASCENDS CarbonHawk Experiment Simulator (ACES)** is an Instrument Incubator Program (IIP) project that seeks to advance technologies critical to measuring atmospheric column carbon dioxide (CO_2) mixing ratios from space in support of the ASCENDS (Active Sensing of CO_2 Emissions over Nights, Days, and Seasons) Decadal Survey mission:

- Passive satellite measurements cannot make retrievals of CO_2 column densities to the surface at night, at high latitudes (i.e. northern Europe during winter and over the poles), and through cirrus clouds, high optical depth aerosols, or in presence of scattered clouds.
- Active measurements using lidars do not have these limitations, and they can therefore fill these data gaps and aid in the refinement and understanding of the global carbon cycle budget.



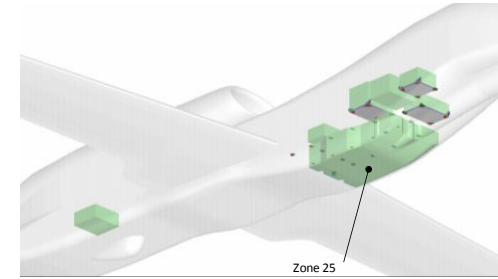
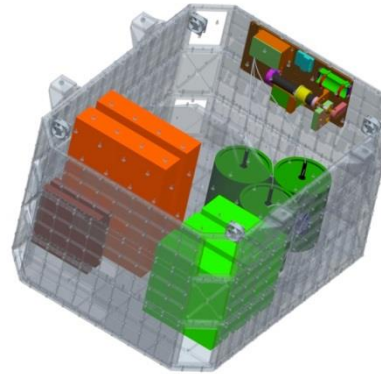
Technology Challenges

ACES is advancing 4 key technology areas:

- (1) Enable development of more advanced modulation waveforms with improved detector subsystem
- (2) Increase transmit power and efficiency for CO₂ measurements at 1.57 microns using commercial amplifiers with stable, tunable laser-line locking system
- (3) Demonstrate column CO₂ retrievals with alignment of multiple laser beams transmitting simultaneously in the far-field for scalability to space
- (4) Continue refining CO₂ column retrieval algorithms in the presence of low optical depth clouds and distributed scattering layers (i.e. aerosol layers)

ASCENDS Mission Development

Current



**Today: MFL and ACES
instruments in DC-8 racks**

**Size = 100" x 43" x 24"
Mass = 787.2 lb.**

**Size = 44" x 34" x 24"
Mass = 317.1 lb**

Global Hawk



Future

**TBD:
ISS Tech
Demo?**



**TBD:
ASCENDS
mission**





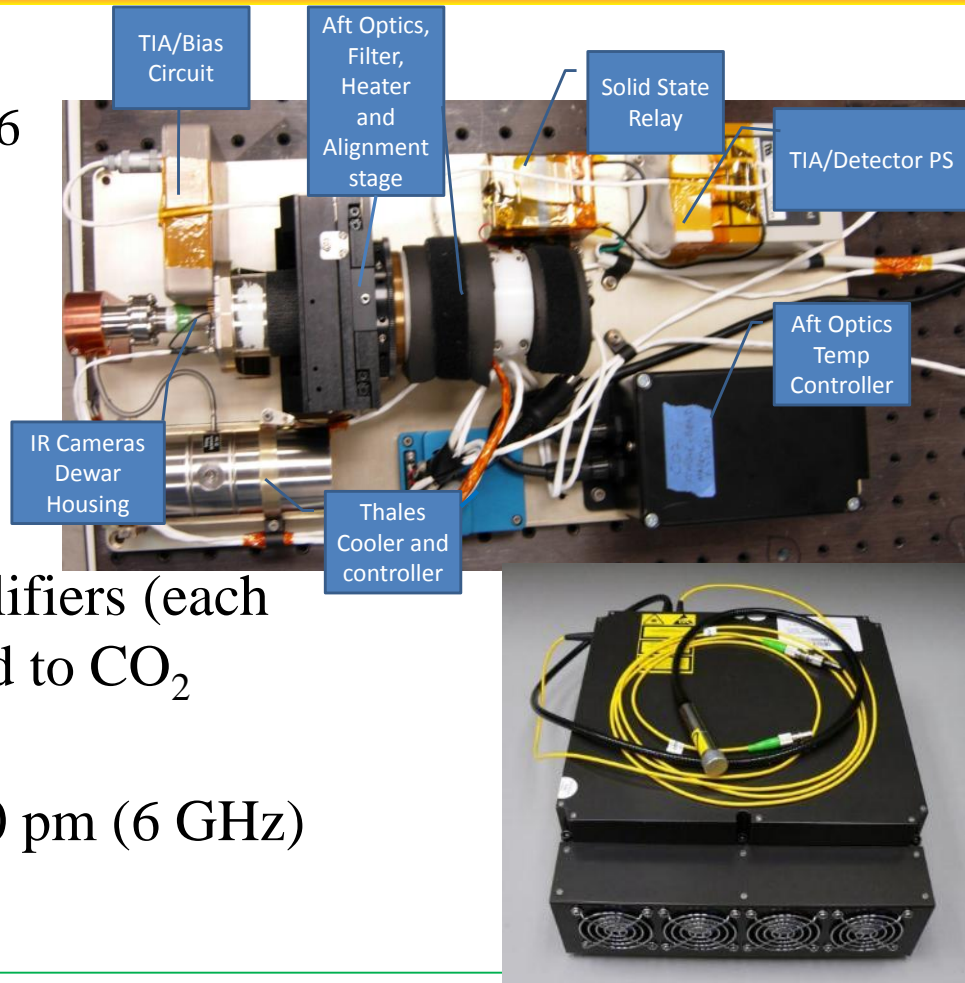
Transmitters and Telescopes

DRS Technologies HgCdTe array

- ~4.9 MHz bandwidth @ gain of 10^6
- Continuously cooled at 77 K
- NEP: $2.4 \text{ fW/Hz}^{1/2}$
- Excess Noise Factor: ~1.1
- Tested with MFL on DC-8 in 2013

Transmitters:

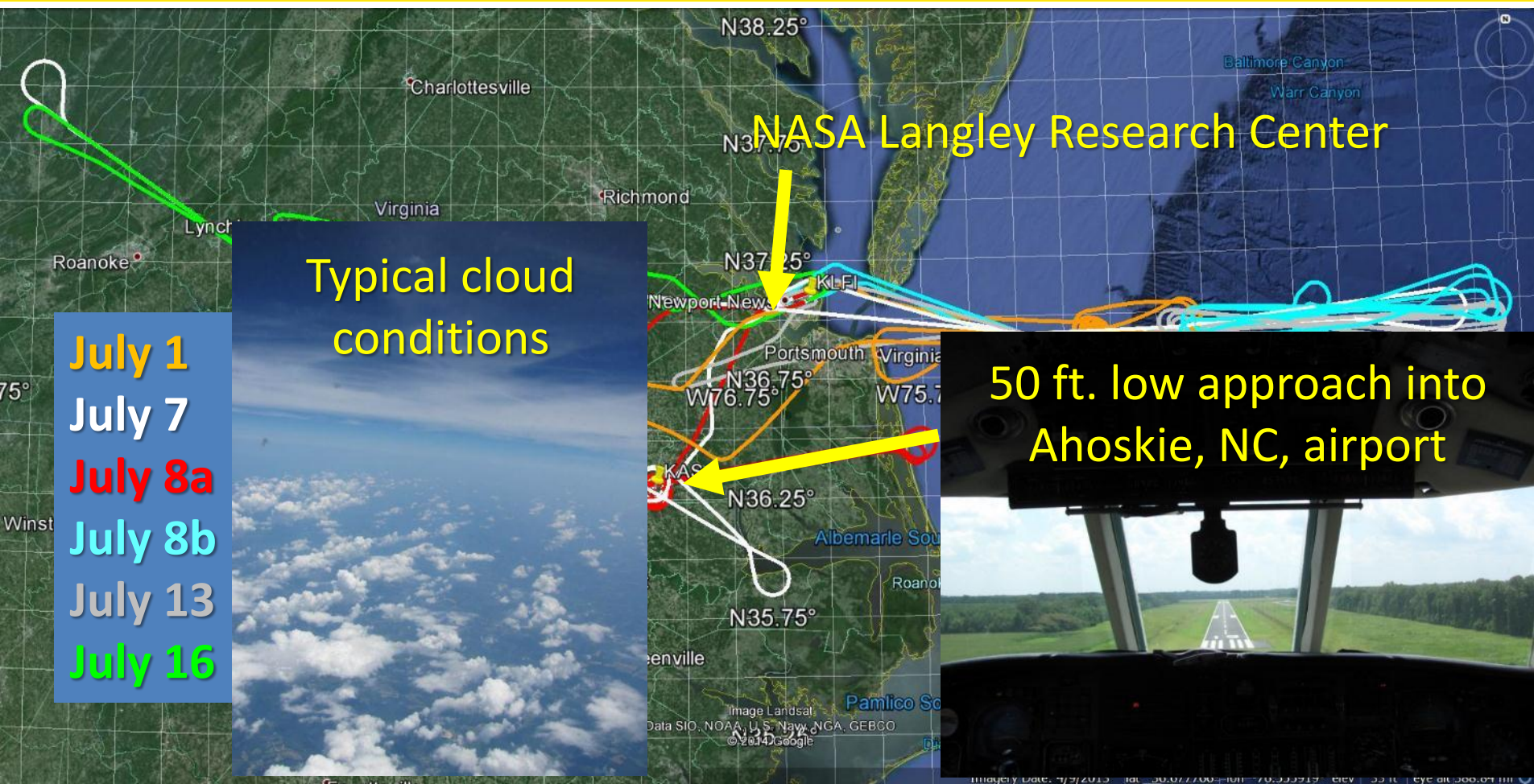
- Three Erbium-Doped Fiber Amplifiers (each 10 W average, 20 W peak) locked to CO_2 absorption line (1.57 microns)
- Wavelength tunable within $\pm 50 \text{ pm}$ (6 GHz) from line center



Combination of low-noise detector, higher power transmitters, and larger collection apertures improves signal-to-noise ratio; increased bandwidth allows for use of more advanced modulation waveforms.



Flight Summary: 17.4 flight hours



Data recorded at multiple altitudes over land and ocean surfaces with and without intervening clouds.